Army Research Laboratory

Multi-Purpose Acoustic Target Tracking For Additive Situational Awareness

by Latasha Solomon

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Multi-Purpose Acoustic Target Tracking For Additive Situational Awareness

Latasha Solomon
Sensors and Electron Devices Directorate, ARL

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14. ABSTRACT
The U.S. Army Research Laboratory (ARL) has successfully used acoustics to detect, localize, and track potential threats. This information has provided a wealth of information to the individual Soldier by supplying actionable situational awareness. Two particular scenarios where these algorithms would provide useful intelligence relate to collision avoidance and monitoring drug trafficking. This research analyzes the acoustic signals of several aerial platforms in an attempt to track each target of interest. Results of different signal-processing techniques—conventional beamformer via minimum variance distortionless response (MVDR) and a Least-Squares (L-S) Estimator using time difference of arrivals (TDOA)—are compared and contrasted. Application of a Kalman filter to the direction of arrival (DOA) estimates is explored. The results found that although neither algorithm performed flawlessly, the TDOA L-S method required less computation time and the MVDR algorithm produced more accurate tracking. The Kalman filter also improved results when used with both techniques.

15. SUBJECT TERMS
Acoustic detection, collision avoidance, localization

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Contents

List of Figures

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Executive Summary

The U.S. Army Research Laboratory (ARL) has successfully used acoustics to detect, localize, and track potential threats. This information has provided a wealth of information to the individual Soldier by supplying actionable situational awareness. Two particular scenarios where these algorithms would provide useful intelligence relate to collision avoidance and monitoring drug trafficking. This research analyzes the acoustic signals of several aerial platforms in an attempt to track each target of interest. Results of different signal-processing techniques—conventional beamformer via minimum variance distortionless response (MVDR) and a Least-Squares (L-S) Estimator using time difference of arrivals (TDOA)—are compared and contrasted. A Kalman filter was applied to the direction of arrival (DOA) estimates to more accurately track the signal of interest.

The Kalman filter algorithm proved efficient in smoothing the overall results while minimizing the effects of outliers due to wind noise and microphone vibrations. Although neither algorithm performed flawlessly, the TDOA L-S method proved superior based on computation time and the MVDR algorithm produced more accurate tracking of the specified target.

The following future work is required:

- Fine tuning the filters to include position as well as velocity for the Kalman state space model, which would further increase the signal-to-noise ratio.
- Fusing DOAs to include an elevated array to determine a precise location of threat for a given instance in time.
- Incorporating a three-dimensional tracker that includes target height information.

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1. Introduction

Acoustic arrays with known locations can detect mortar, improvised explosive device (IED), and rocket points of origin and impact. Research has proven that this same technology can also detect and track vehicles, unattended aerial vehicles (UAVs), and helicopters (*1*). This information is especially useful for collision avoidance. Collision avoidance is a concern for all aircraft that need to detect hazardous terrain or obstacles in sufficient time to accomplish clearance maneuvers. This technology is even more demanding for helicopters, as their unique capabilities result in extensive operations at low altitude, near terrain and hazardous obstacles.

Military helicopter pilots often fly below tree level, facing unique guidance and control tasks such as aircraft concealment, obstacle avoidance, and real-time mission planning. These tasks require a high degree of pilot concentration, which intensifies during bad weather and stressful tactical situations. Automation of some of these tasks can reduce pilot workload, while enhancing safety (*2*).

As mentioned, acoustics can also be used to track vehicles used to transport contraband and illegal aliens. Documents suggest organized crime leaders have airplanes, boats, and vehicles at their disposal (*3*). It is believed that tracking these targets will aid in increasing homeland security.

2. Signal Processing

The initial algorithm applied to the aerial targets of interest is the conventional beamformer via minimum variance distortionless response (MVDR). This optimum distortionless filter assumes that the noise is a sample function of a random process and the signal of interest is an unknown nonrandom signal propagating along some known direction. This guarantees that any signal propagating along the specified direction will pass through the filter undistorted and the output noise is thus minimized (*4*). The optimal estimate of the wave number spectrum is given by

$$P_o(k,f)=\{\mathbf{v}^H(k,f)\mathbf{S}^{-1}(f)\mathbf{v}(k,f)\}^{-1}, \tag{1}$$

where $\mathbf{v}(k,f)$ is the array manifold vector for a plane wave with a wave number k and $\mathbf{S}$ is the correlation matrix. The min and max frequencies, f, used were 10 and 200, respectively. These frequencies were chosen to eliminate some of the dominant wind noise while focusing on the fundamental and corresponding harmonics of the main and tail rotor of the helicopter. This algorithm was capable of localizing on the targets of interest pretty well; however, computation time was slow.

The next algorithm considered was a Least-Squares (L-S) Estimator using time difference of arrivals (TDOA). The L-S approach chooses the value of θ that best minimizes the squared difference between the given data and the assumed signal. This algorithm preformed slightly less accurately than the prior method; however, calculations were performed in a significantly shorter time frame. The process is described in equation 2:

$$\theta_{L\text{-}S} = P^{+}\hat{\tau} \ , \tag{2}$$

where P represents the difference in microphone locations and $\hat{\tau}$ are the estimated time delays between corresponding microphone locations (*5*).

Due to the noisy measurements obtained via MVDR and L-S direction of arrival (DOA) estimates, a Kalman filter was applied to the results in an attempt to smooth the signal and increase the overall localization accuracy. The Kalman filter address the general problem of trying to estimate the state $x \in R^n$ of a discrete-time controlled process that is governed by the linear stochastic difference equation

$$x_k = Ax_{k-1} + Bu_{k-1} + w_{k-1}, \tag{3}$$

with a measurement $z \in R^m$, i.e.,

$$z_k = Hx_k + v_k \,. \tag{4}$$

The random variables w_k and v_k represent the process and measurement noise, respectively. They are assumed to be independent of each other, white noise, and normal probability distributions:

$$p(w) \sim N(0,Q), \tag{5}$$

$$p(v) \sim N(0,R) \ [6]. \tag{6}$$

The process noise covariance, Q, is assumed to be constant and the measurement noise covariance, R, is updated with each time step as function of the standard deviation of each measurement. The measurement noise covariance determines how much information from the sample is used. If R is high, the Kalman filter assumes the measurement is not very accurate. When R is smaller, the filter output follows the measurement more closely. The input noise covariance contributes to the overall uncertainty of the estimate. The Kalman filter output when Q is large tracks large changes in the actual output more closely than when Q is small. Consequently, there is a performance trade-off between tracking and noise in the output in the choice of Q for the Kalman filter (*7*).

The $n \times n$ matrix A in the difference equation relates the state at the previous time step k-1 to the state at the current step k, in the absence of either a driving function or process noise. In this research, it is assumed that only the direction of arrival is observed, and its rate of change is

unknown. Therefore, A is a constant, scalar 1. The n×1 matrix B relates the optional input control input $u \in R^l$ to the state x; for this research B is assumed to be 0. The $m \times n$ matrix h relates the state to the measurement z_k and assumed to be a constant, scalar 1.

Finally, a modified Kalman filter was applied to the MVDR and L-S data. This method updates the current estimate, k, if the standard deviation between two consecutive angles of arrivals is less than a predetermined threshold, otherwise the current estimate, k, remains the same as the previous, k-1. It is assumed that the DOA is either erroneous or relates to another target.

3. Experimental Procedures and Results

Four tetrahedral arrays were used to collect an hour of acoustic data relating to the flight path of a helicopter. These arrays were spaced approximately 1.5 km apart in a square configuration. To get a better feel for the spectrum of the helicopter with respect to the surrounding background noise, the spectrogram was applied to the acoustic data acquired from one of the sensor arrays as illustrated in figure 1. The array was capable of detecting the helicopter for the duration of the test with a maximum range of approximately 5 km. The spectrogram indicates that there is a relatively high signal-to-noise ratio relating to the helicopter's fundamental frequency and its first few harmonics. Previous research has shown that as sound propagates over the ground, there will be some attenuation because of acoustic energy losses due to ground impedance absorption, terrain and vegetation effects, and multipath. Higher frequencies are almost always attenuated more than lower frequencies (*8*).

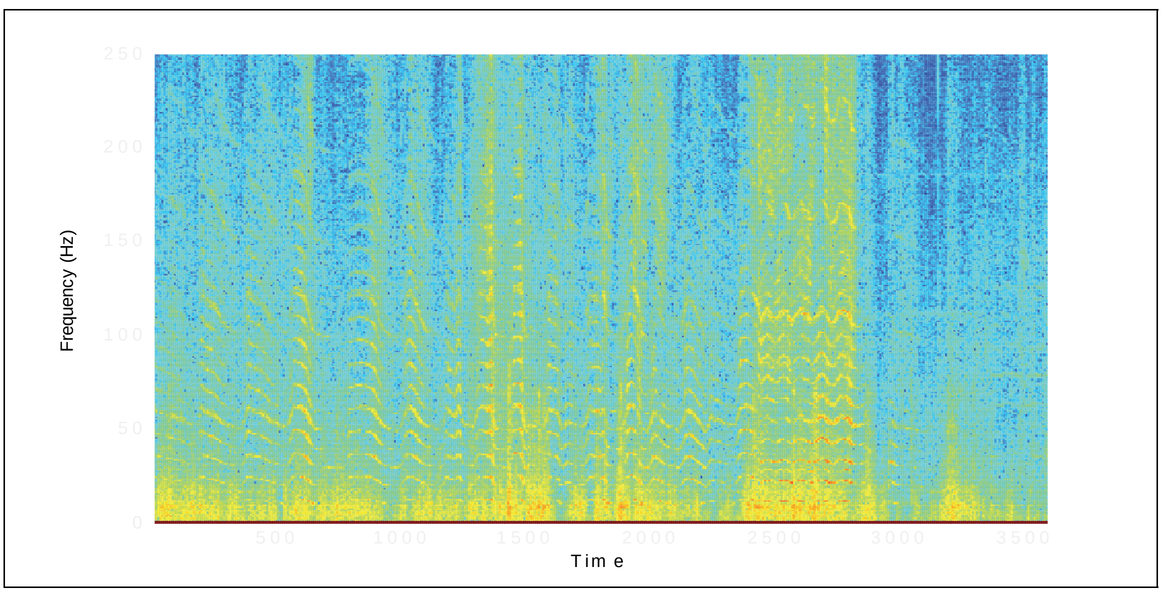

Figure 1. Spectrogram of acoustic data acquired from one sensor array.

Figure 2 illustrates calculated DOA estimates of acoustic data simultaneously collected from four known sensor locations. These results were obtained using MVDR, where the black, green, red, and blue lines represent the true, observed, Kalman filtered, and modified Kalman filter data, respectively.

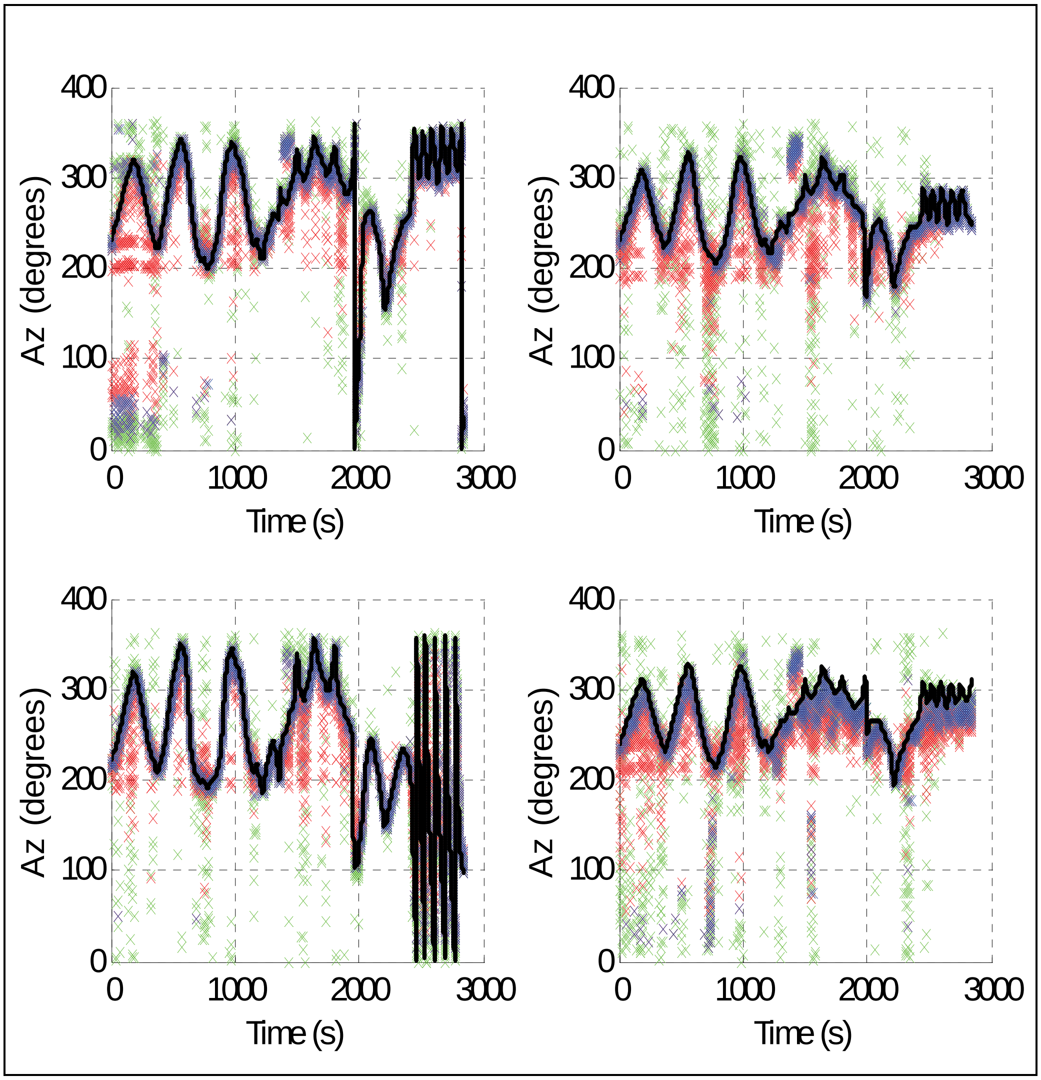

Figure 2. Direction of arrivals computed simultaneously for four sensor arrays via MVDR.

Given the information above and the known sensor locations, triangulation can be used to successfully track the helicopter's two-dimensional (2-D) coordinates. This information is of value for collision avoidance in areas where hazardous terrain, inconspicuous foreign objects, and sand storms exist.

Figure 3 illustrates the TDOA L-S results for the same set of data, where the black, green, red, and blue lines represent the true, observed, Kalman filtered, and modified Kalman filtered data, respectively.

This set of data proved to be slightly less accurate and is believed to be a result of a pair wise time delay estimation of a narrow band signal resulting in two ambiguous bearings. Computation time is significantly faster; L-S data can be calculated 10–12 times faster than MVDR data. Application of the modified Kalman filter significantly improves DOA estimates for both the MVDR and L-S approaches.

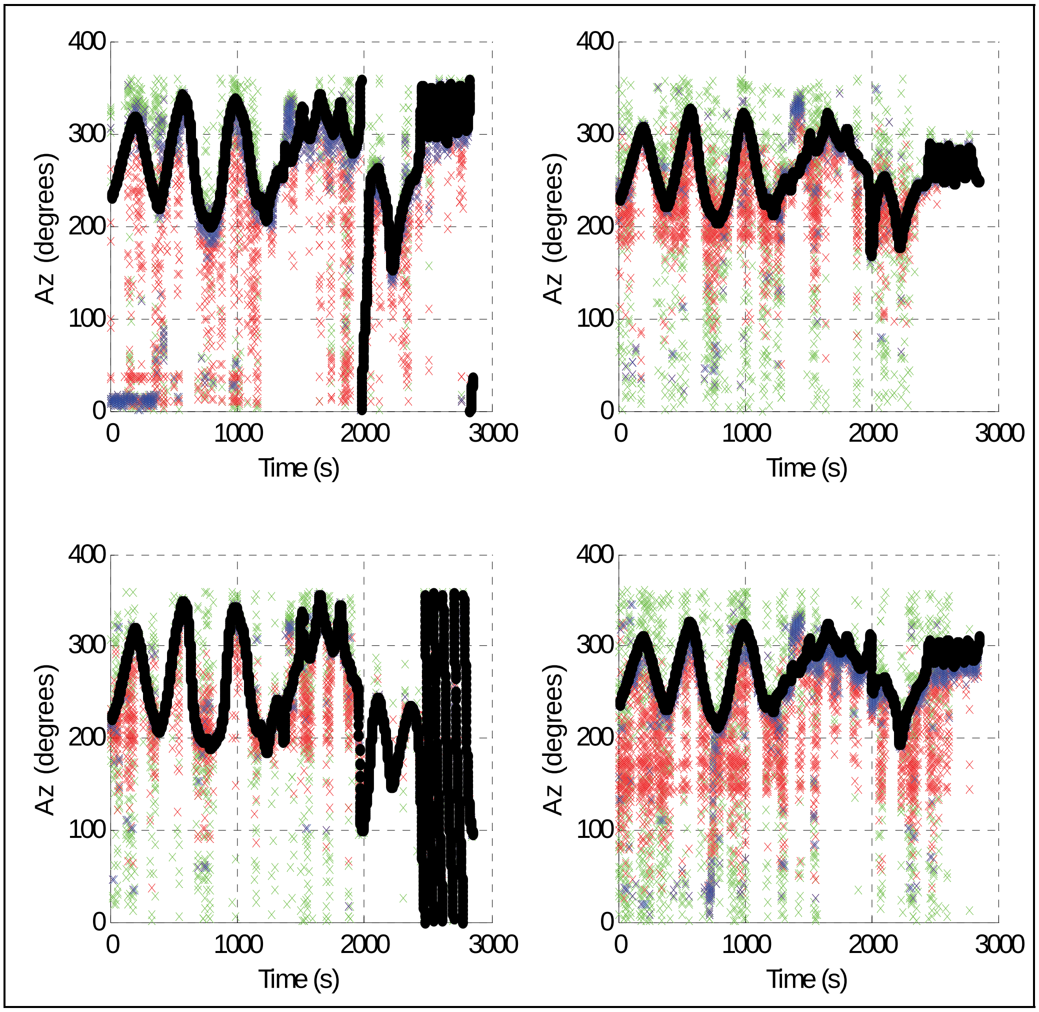

Figure 3. DOAs computed simultaneously for four sensor arrays via L-S approach.

Comparison of figures 2 and 3 indicates that there is a substantial amount of spurious detections via both algorithms. Contributing factors are thought to be wind noise, microphone vibration, and surrounding targets not associated with testing. Elevation angles were also calculated using both algorithms; however, these proved to be unsatisfactory when comparing to truth data and thus were omitted from this report. These results are thought to be a result of sound waves reflecting and refracting off of the ground near the sensor locations. Previous research has shown that elevated arrays, more specifically those on an aerostat platform, increase the signal-to-noise ratio, thereby increasing range detection and overall system accuracy when estimating azimuth and elevation (*9*).

The modified Kalman filtered data was then used to triangulate the 2-D grid coordinates of the target of interest. For tether avoidance application, the user is primarily interested in threats approaching the tether within a 1 km radius. Figure 4 illustrates the estimated grid solution when the helicopter is within a 2 km radius of a specific location. The black lines correspond to the truth data and the green and blue lines correspond to the MVDR and L-S estimate, respectively. No estimate is calculated when the distance between the target and sensor is less than 20 m. Again, the MVDR is most accurate in estimating the targets true location.

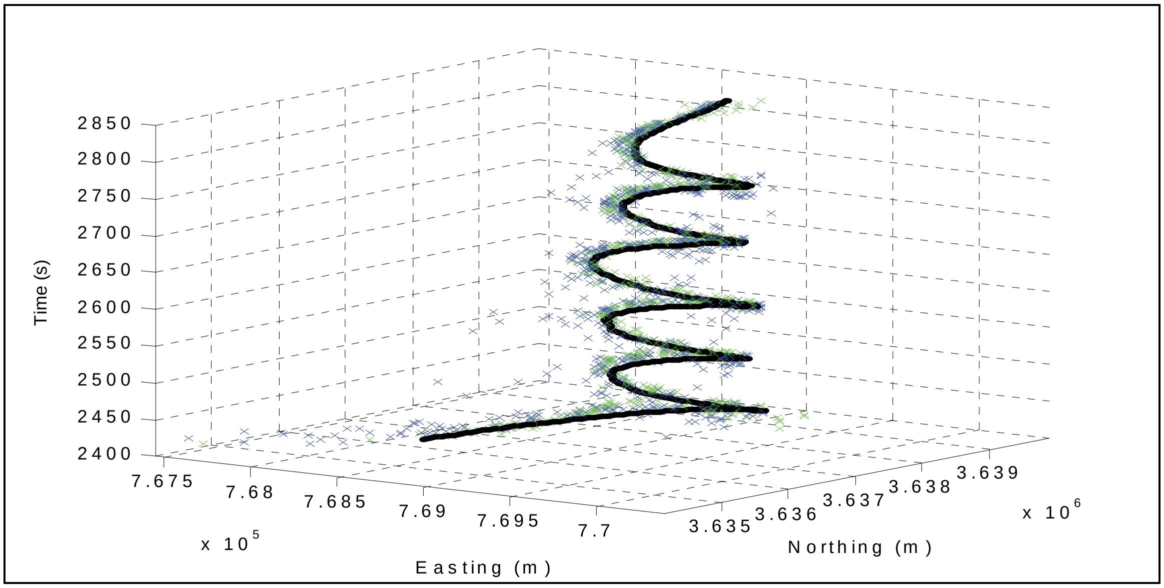

Figure 4. Estimated 2-D tracking for MVDR, L-S, and truth vs. time.

Figure 5 illustrates the true distance of the helicopter's flight path in figure 4 with respect to a known location that is then calculated and compared to the distance computed for the MVDR and L-S. The black lines correspond to the truth data and the green and blue lines correspond to the MVDR and L-S estimates, respectively. In general, the L-S tends to overestimate the distance of the helicopter. This is a direct effect of the DOA estimates; even slight variations in DOA estimation can result in significant tracking errors.

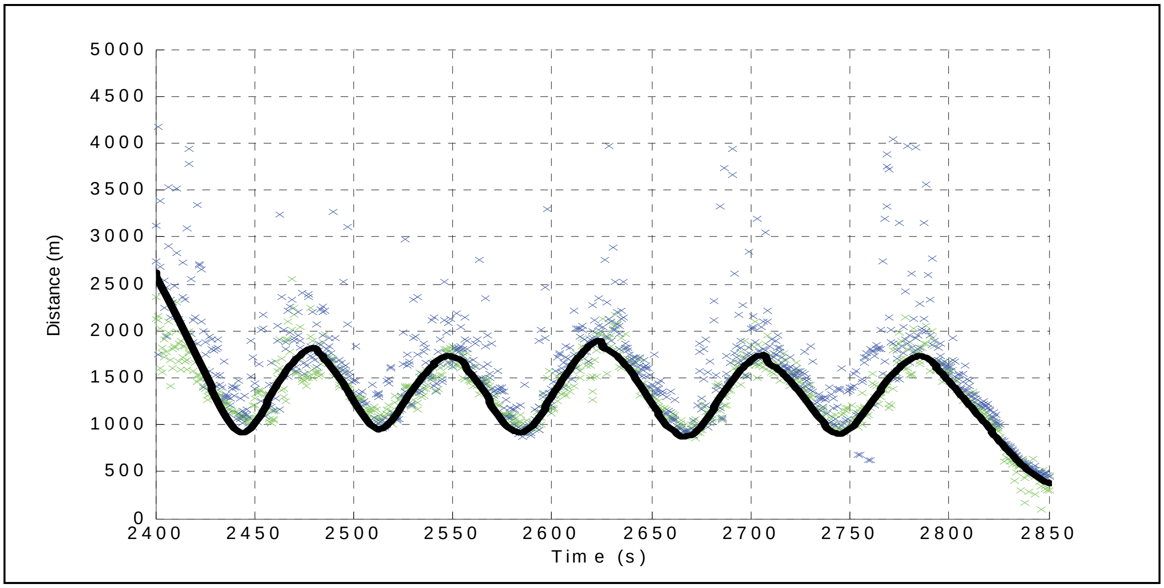

Figure 5. Estimated distance of MVDR and L-S algorithm compared to true distance.

The green and blue lines in figure 6 correspond to the relative tracking error for the MVDR and L-S, respectively. The error was also calculated for distances within 2.5 km (figure 6); this error is expected to decrease with increased array alignment accuracy and for targets within the 1 km range of interest.

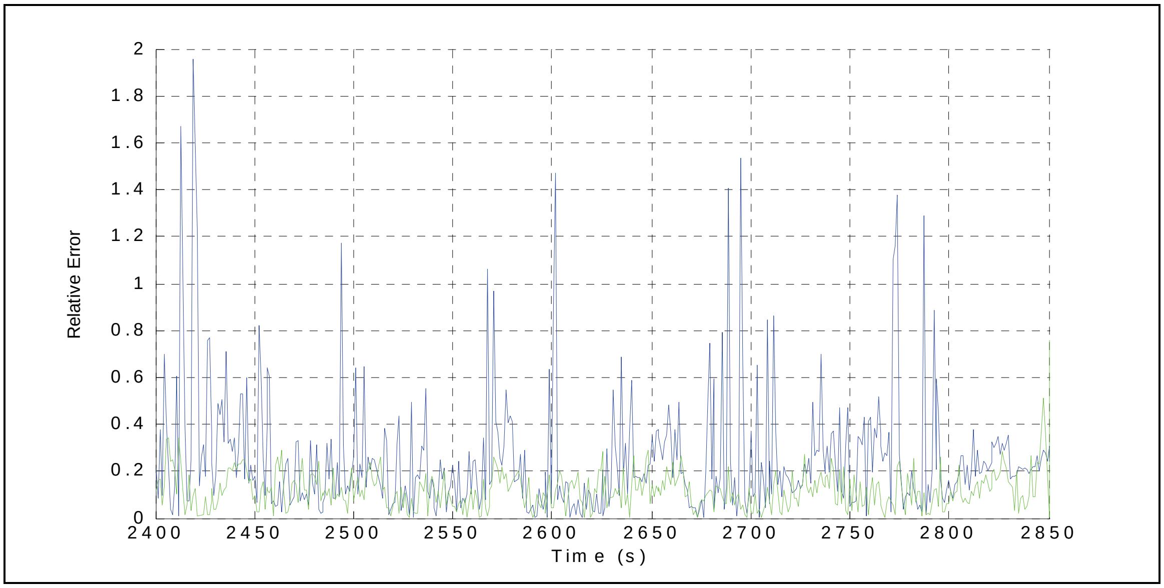

Figure 6. Relative tracking error for distances below 2.5 km.

These same algorithms have proven successful in tracking two separate small planes, which are similar to those that may be used in drug trafficking and smuggling scenarios. This information would be extremely useful for homeland security and protecting our borders. Figure 7 contains the estimated direction of arrivals for the two aircraft for a 1-h duration.

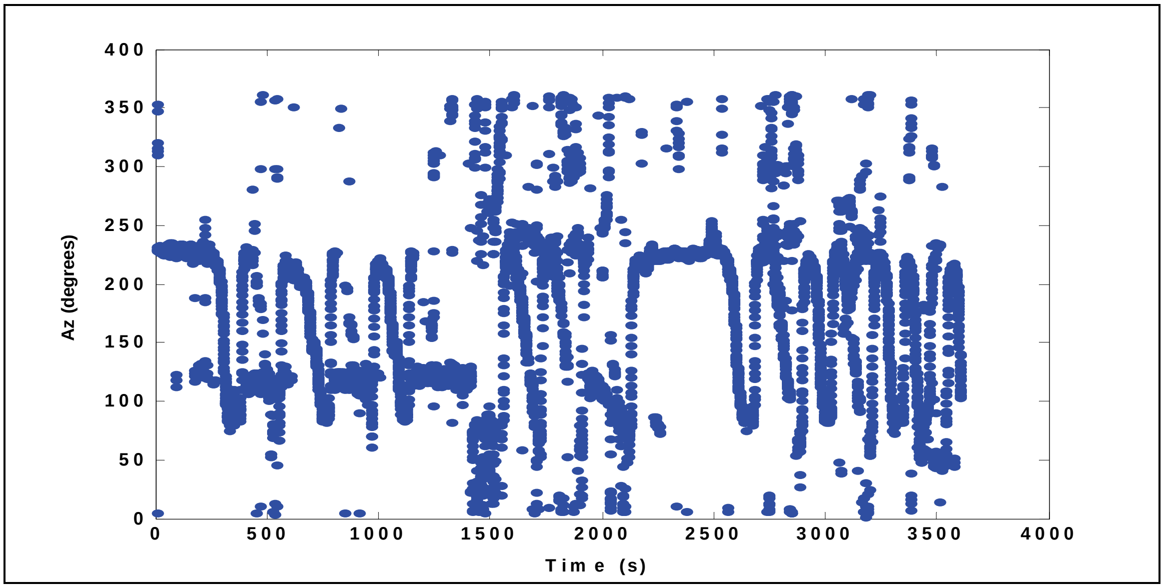

Figure 7. DOA computed via MVDR for two small aircraft.

No global positioning system (GPS) data relating to the true path of either of the planes were available at the time of this report; however, I believe it is valuable to include figure 6 based on the prior results presented. Hand written notes were taken and appear to pretty accurately detail the measurements illustrated in figures 6 and 7. Though figure 6 appears to be somewhat "noisy," it should be noted that ground vehicles, personnel, and other aircraft were in the immediate vicinity. A stationary car has its engine running and the algorithm detects this in both sets of data around 125^{o}. In figure 7, approximately half way into the file, both planes are detected flying simultaneously. Figure 8 shows a spectrogram of the last 10 min of data, highlighting the aircraft taxiing, taking off and landing, as well as in flight.

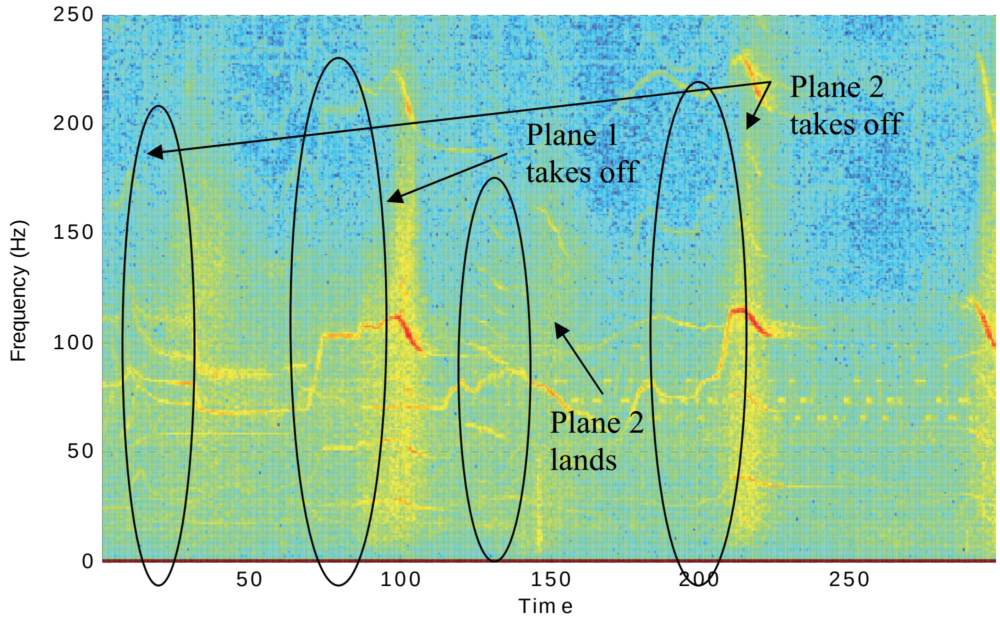

Figure 8. Spectrogram of two small aircraft taxiing on the runway and in flight.

4. Conclusion

This research has proven successful in tracking aerial vehicles. Two conventional signal-processing techniques were applied to the data in an attempt to estimate DOAs. A Kalman filter was applied to the DOA estimates to more accurately track the signal of interest. This algorithm proved efficient in smoothing the overall results while minimizing the effects of outliers due to wind noise and microphone vibrations. Although neither algorithm performed flawlessly, the TDOA L-S method proved superior based on computation time and the MVDR algorithm produced more accurate tracking of the specified target. The research documented in this report is applicable to several applications including, but not limited to, collision avoidance and deterring drug trafficking through tracking.

The following future work is required:

- Fine tuning the filters to include position as well as velocity for the Kalman state space model, which would further increase the signal-to-noise ratio.
- Fusing DOAs to include an elevated array to determine a precise location of threat for a given instance in time.
- Incorporating a three-dimensional tracker that includes target height information.

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